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CONTINUOUS HIGH-VELOCITY JET EXCAVATION.

PHASE II

Bendix Research Laboratories

PREPARED FOR

Advanced Research Projects Agency

Bureau of Mines

October 1973

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FINAL REPORT

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Amount of Contract: $122,372
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Principal Investigator:

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This report describes the development of a mobile, fluid-jet, rock fracturing system suitable for performing the field testing required to investigate the feasibility of excavation of *in situ* rock structures by the action of continuous, high-pressure, fluid jets. Program scope included the design, manufacture and field testing of a mobile, high-pressure, fluid-jet rock fracturing system. General operating parameters of the system, such as jet pressure level, standoff distance, and feedrate, are based on data gained from laboratory testing previously conducted by Bendix under contract to the Bureau of Mines. Testing of *in situ* rock excavation characteristics was conducted at a field site by traversing the high-pressure jet past the rock face. Supply pressure, traverse speed and standoff distance were the recorded variables. Test objectives were (1) to confirm the Phase I laboratory data in the field and (2) to determine the reduction of specific energy achieved by utilizing mechanical breaking devices. The scope of the current program did not include optimization of fluid-jet parameters and mechanical breaking devices to minimize specific energy for the hybrid system.

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SECTION 1

SUMMARY

The objective of this effort was the development of a mobile, mechanically assisted, fluid-jet, rock fracturing system suitable for performing the field testing required to investigate the feasibility of excavation of *in-situ* rock structures by the action of continuous, high-pressure, fluid jets. Program scope included the design, manufacture and field testing of the fluid-jet rock fracturing system. General operating parameters of the system, such as jet pressure level, standoff distance, and feedrate, were based on data gained from laboratory testing previously conducted by Bendix under contract to the Bureau of Mines.

The results of the laboratory testing indicated that the required specific energy was too high to justify the use of an excavation system utilizing jet action alone instead of a conventional tunnel excavator. Test data was utilized, however, in the generation of a mechanically assisted, fluid-jet, excavation-machine concept which was predicted to have a significantly reduced overall specific energy. It was expected that further laboratory and field testing would be required to optimize the specific energy for a mechanically assisted jet excavator. The mobile rock-excavation system was designed to include a mechanical rock-fragmentation device.

Testing of both *in-situ* rock excavation characteristics and the efficacy of the mechanical fragmentation device was conducted on *in-situ* Barre Granite by traversing the high-pressure jet and fragmentation device over the rock face.

Supply pressure, traverse speed and standoff distance were the recorded variables. Test objectives were (1) to provide field confirmation of the Phase I laboratory data and (2) to determine the reduction of specific energy achieved by utilizing mechanical breaking devices. Although the field test data have a lower confidence level than the laboratory data, the field test data indicate that the specific energy of excavation of *in-situ* rock is lower than that determined during laboratory testing. The lower level of confidence in the field test data is occasioned by the fewer number of runs, compared to the laboratory data, as well as the difficulty in conducting accurate kerf volume measurements in the field. Efficiency data on the mechanical fragmentation device indicated that it provided some decrease in specific energy over the unassisted-jet data; however, test data was not sufficiently conclusive to verify the amount of the decrease. The scope of the current program did not include optimization of fluid-jet parameters and mechanical breaking devices to minimize specific energy for the hybrid system.

Further laboratory and field testing will be required to accomplish such optimization, permitting construction of systems capable of rapid low-cost excavation for both civil and military applications including underground relocation of utilities, transit systems and other installations for greater protection from destructive surface intrusion as well as more productive utilization of surface areas.

No inventions were conceived or reduced to practice under the contract.

SECTION 2

RESEARCH PROGRAM AND PLAN

Based on the results of Phase I of this program, indicating that the specific energy of fluid jets alone is too high for practical application to rock fracturing, a concept developed during Phase I for a mechanically assisted fluid-jet excavation system was implemented. Implementation consisted of detailed design, fabrication and assembly of component parts to produce a mobile system comprised of fluid jets for cutting kerfs in the rock surface and mechanical cutters for breaking the rock between kerfs. Finally, the completed hybrid system was field tested at a granite quarry for the purpose of verifying laboratory data obtained in Phase I and evaluating the predicted improvement of the hybrid system over the pure fluid-jet systems.

The specific energy calculated for the hybrid system did not represent the optimum specific energy for such a system because the jet operating parameters employed in the analysis were those which gave the minimum specific energy for pure jet excavation. These parameters were also observed to give the shallowest kerf depths. As kerf depth is increased, the spacing between kerfs can also be increased, thereby increasing the volume of material removed by mechanical action. Since the jet excavation energy constitutes the majority of the energy input to the rock, the maximum overall efficiency for a hybrid system may be obtained at the operating parameters which produces the deepest kerf, even though the jet excavation portion of the process is not operating at its minimum specific energy. The current effort included fabrication of a mechanical breaking device, thus permitting determination of specific energy for excavation of *in-situ* rock structures.

SECTION 3

MOBILE ROCK-FRACTURING SYSTEM

The mobile, fluid-jet, rock-fracturing system, shown in Figure 1, consists of four major elements: a 70,000 psi intensifier, a mechanical rock-fracturing device, a mobile base and traversing system, and a 5,000 psi hydraulic supply. All major elements were assembled from commercially available components.

3.1 INTENSIFIER

A high-pressure intensifier capable of delivering a maximum flow of one gallon per minute at pressures up to 70,000 psi was required for the mobile, fluid-jet, rock fracturing system. Such a unit had been introduced for commercial sale by Kobe, Inc., of Huntington Park, California. The unit had been tested by the manufacturer and was warranted to give adequate life under the pressure and flow conditions required for the mobile rock-fracturing system. In addition, the relatively low weight of the unit substantially reduced the mounting and manipulation problems associated with other commercially available intensifier designs considered, when used in a mobile machinery application such as the rock fracturing device.

The Kobe 70,000 psi intensifier is a double-acting, hydraulically powered unit designed to operate on an input pressure to 5,000 psi and to provide a high-pressure discharge up to 70,000 psi at a flow of 1 gallon per minute. The input end of the unit has a pilot-operated reversing valve which is hydraulically actuated; the input piston rod has a floating connection with a high-pressure plunger at each end of the unit. The discharge of the two high-pressure cylinders is connected via a surge chamber which reduces the discharge pulse to a value of 2,000 psi maximum at 70,000 psi in water with soluble oil. The unit may be operated on any hydrocarbon or synthetic oil, or on water with a minimum of 3 percent lubricant, such as soluble oil. Overall unit length is 9 feet 4 inches and the total weight is 450 pounds. The general intensifier design is based on earlier designs employed for many years in oil-well pumping systems at pressures of 5,000 to 30,000 psi. The manufacturer's test data and previous experience with lower pressure units indicate that a maintenance interval of 750 hours on the pump section and 3,000 hours on the hydraulic section can be expected at a discharge pressure of 70,000 psi. Lower pressure operation increases the maintenance interval significantly; for example, at a discharge pressure of 40,000 psi, the predicted maintenance intervals are 2,000 hours for the pump section and 6,000 hours for the hydraulic section.

Water for the intensifier is stored in a 35-gallon holding tank and is pressurized to the required 100 psi using the air supply required for

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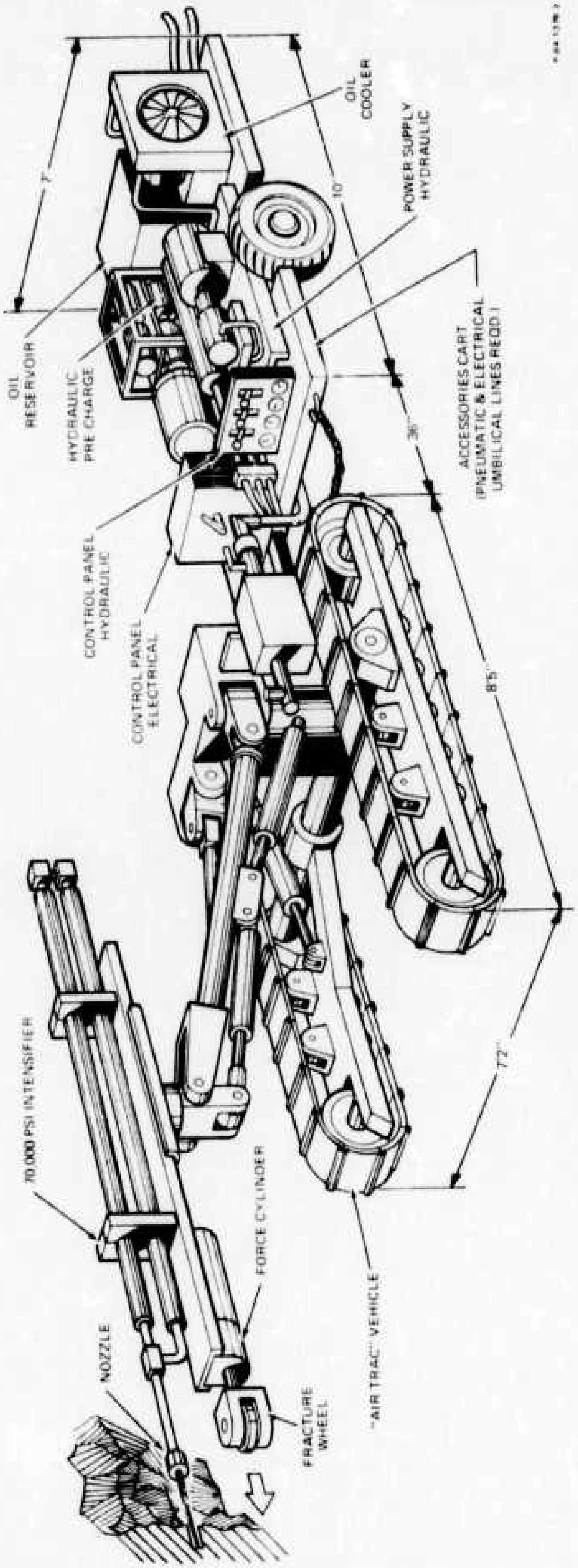

Figure 1 - Mobile, Fluid-Jet, Rock-Fracturing System Design

operation of the crawler vehicle drives. Advantages of this system over previously considered water supply methods are simplicity and both lower initial and operating costs.

3.2 MECHANICAL FRAGMENTATION DEVICES

Two types of mechanical rock-fracturing wheels were provided with the rock fragmentation system: a disc-type cutter and a tungsten carbide button cutter.

The disc cutter design closely followed the concepts advanced in the final report of Continuous High Velocity Jet Excavation - Phase I, Contract No. H0220034, in which the cutter would be run along the jet-excavated kerf in order to remove the remaining rock by wedging action.

A tungsten carbide button cutter, of the design utilized on tunnel moles, was manufactured for use in attempts to induce spallation of rock remaining between two adjacent jet kerfs. Evaluation of several commercially available cutters dictated the use of a manufactured design because of cost and weight considerations.

The mechanical fracturing devices are forced against the rock face by means of a piston assembly attached to the intensifier mount. The piston assembly is loaded with a regulated pressure in order to provide a constant force on the fracturing device regardless both of irregularities in the rock face and of the changing distance to the face occasioned by the arc in which the fracturing device travels. Force available to load the cutter wheels is a maximum of approximately 3500 pounds.

3.3 MOBILE BASE AND TRAVERSING SYSTEM

An evaluation of commercially available self-propelled crawler bases resulted in a decision to purchase a Model ATD 3100 from the Drill Carrier Co. The basic crawler assembly consists of a heavy-duty frame to which are mounted a pair of air motor-driven tracks. Controlled track oscillation on uneven surfaces is attained by positive-acting hydraulic cylinders, which insure both good ground contact and stability. Each track is operated independently by an air motor to provide maximum mobility. Manually actuated valves for each motor drive, and the boom and positioner controls, are located at the rear of the unit.

Another standard feature of the ATD Model 3100 Crawler is a jib-type boom with an integral drill positioner mounted to the crawler frame. Power for the boom is supplied by an air motor-driven hydraulic power supply which is an integral part of the boom assembly. Total air consumption, when operating all systems simultaneously, is 600 cfm at 100 psi. The 70,000 psi intensifier and mechanical fragmentation device are mounted on the positioner assembly at the end of the boom and controlled by manually actuated valves at the rear of the assembly. Modifications were completed in the crawler hydraulic system to permit operation powered by either the air-driven hydraulic pump or the hydraulic power supply provided to drive the high-pressure intensifier.

Several different concepts were evaluated for traversing the intensifier across the rock face. One approach evaluated for the final design included a separate nozzle-drive mechanism which incorporated a flexible 70,000 psi link. Although this approach would minimize variations in both standoff distance and speed, calculations indicated that commercially available super-pressure tubing would have an unacceptably short life if subjected to both an internal pressure of 70,000 psi and bending. For this reason, the positioning device for traversing the intensifier across the rock face consists of a jib-type boom as originally proposed. The boom assembly is capable of moving approximately ± 40 degrees from the base centerline, as well as +45 degrees from the horizontal plane. These motions of the boom may be employed to provide gross positioning of the intensifier assembly with respect to the rock face. The hydraulic positioning assembly, mounted on the boom, was modified to traverse the intensifier at a constant predetermined rate through approximately ± 10 degrees from the boom centerline. Direction of motion is controlled by a manually operated 4-way valve and speed control is achieved by employing a calibrated, manually adjustable flow control valve. The hydraulic positioning assembly also provides sufficient rotation with respect to the horizontal plane to maintain perpendicularity between the intensifier and the rock face in all boom positions. This operation is not automatic and manual adjustment of boom perpendicularity is required following a significant change in boom position. The traversing system is designed to provide sufficient motion to produce a series of parallel horizontal kerfs approximately 2.0 feet long.

3.4 HYDRAULIC SYSTEM

The 5,000 psi hydraulic system is employed to drive the intensifier and power the traversing system. All elements are commercially available, off-the-shelf components. All control valves for the hydraulic system are manually operated and are located at the rear of the crawler assembly in near proximity to the standard crawler and boom controls.

The hydraulic system incorporates a 5,000 psi, 30 gpm, pressure compensated, variable-displacement hydraulic pump. The pressure compensating feature automatically regulates the flow delivered by the pump by changing the length of stroke of the pumping pistons. The stroke change is controlled solely by the system pressure in such a manner that when the pump is operating at a pressure less than the maximum setting of the compensator, the pump delivers full flow. When the compensator pressure setting is reached, the piston stroke is automatically reduced to that which will provide the amount of flow required to maintain pressure throughout the working system. The pressure at which the changes take place is regulated by adjustment similar to the control of a relief valve. The variable-displacement pump with a pressure compensated control was chosen to minimize heat input to the working fluid. Because the entire system is mobile, the size of the reservoir is limited by

envelope and weight considerations. To minimize the possibility of overheating the hydraulic fluid, all oil returning to the reservoir passes through a motorized, air-cooled heat exchanger. Two accumulators are included in the system to minimize pressure and flow variations caused by intensifier or traversing system operation. An integral, low-pressure, hydraulic boost pump is included to provide flow in excess of that required by the main pump to prevent inlet cavitation. The excess flow from the boost system is routed through the relief valve and air-cooled oil cooler, thus providing constant cooling of the hydraulic fluid.

The hydraulic power unit components are mounted on a trailer behind the crawler vehicle and are connected to the crawler by means of flex hydraulic hoses.

The 1,250 psi, 1.5 gpm, air motor-powered, hydraulic system supplied with the crawler base has been retained for powering the boom and positioner when the crawler is disconnected from the intensifier hydraulic system. For normal test operation, however, the crawler positioning systems will be operated at a reduced pressure from the intensifier hydraulic supply.

SECTION 4

SYSTEM TESTS

On-site testing of the rock fragmentation system was completed during June, 1973, at the Smith quarry of the Rock of Ages Corporation in Graniteville, Vermont. The test site, at the U-6 location of the Smith quarry, provided a smooth vertical face approximately 100 feet in height, and was convenient both to quarry air and water supplies and to a derrick for moving the machine system into and out of the quarry pit. Support for system testing was provided by the Rock of Ages Corporation under the direction of Chief Engineer, Donald Bailey.

The rock formation upon which testing was undertaken was Barre granite. Properties of Barre granite, supplied by the Rock of Ages Corporation, and on file with the U.S. Bureau of Mines Twin Cities Mining Research Center, are as follows.

Property	English Units	SI Units
Compressive strength	23.9×10^3 lb/in^2	167 MN/m^2
Density (apparent)	166 lb/ft^3	2.66 g/cm^3
Shear modulus (dynamic)	2.44×10^6 lb/in^2	16.8 GN/m^2
Shear modulus (static)	$2.2\text{-}2.4 \times 10^6$ lb/in^2	15.2-16.9 GN/m^2
Young's modulus (dynamic)	4.41×10^6 lb/in^2	30.4 GN/m^2
Young's modulus (static)	$3.96\text{-}6.41 \times 10^6$ lb/in^2	27.3-44.2 GN/m^2

Testing was conducted upon the riff face.

Test objectives consisted both of confirming, on *in-situ* Barre Granite, the laboratory data gathered during Phase I of the current effort, conducted under previous Contract No. H0210034, and of generation of baseline data on a combination of mechanical and jet fracturing. Although the latter objective was of most significance, contract scope was primarily concerned with design and construction of the experimental system and did not provide for extensive testing.

For all tests, the kerf depth and width was recorded in five locations spaced one inch apart along the kerf direction. These values were averaged, and a rectangular kerf cross section was used in volume determinations. A rectangular cross section was evidenced by almost all of the kerfs produced during the tests. Previous experience during the Phase I effort indicated that determination of the kerf volume by

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measuring the volume of material required to fill it would be impractical for a vertical rock face. For rock removal by the cutter wheels and by interaction between jet kerfs, the percentage of rock removal between the kerfs was estimated by test personnel. Spallation of rock from the face, following cuts in the same area, was not included in the volume determinations; when spallation occurred during a particular test run, the test was rerun in another area of the rock face.

Testing was conducted as described below.

4.1 CONFIRMATION OF PHASE I DATA

From Phase I laboratory data on Barre Granite, optimum specific energy for single cuts occurred at a pressure of about 30,000 psi, a feedrate of about 300 inches per minute, and a standoff distance of 1/2 inch. As with all other rock types, the most efficient cutting occurred with the smallest nozzle, 0.008 inch in diameter. In the kerfing runs using test parameters that yielded the most efficient single cuts, material was excavated between parallel cuts at a maximum spacing of about 0.100 inch. In order to confirm the above data on *in-situ* Barre Granite, an experiment using the following parameters and values was conducted:

Pressure (psi):	30,000, 50,000, 65,000
Feedrate (ipm):	50, 150, 300
Nozzle dia. (in):	0.008, 0.012
Standoff (in):	1 (nominal)

Control of standoff distance in the field tests was hampered by irregularities in the rock face and the fact that the nozzle path followed a large-radius arc. After each run the test parameters were recorded and the excavated volume approximated from width and depth measurements. Energy input was derived from nozzle horsepower and feedrate.

Data from the Phase I confirmation tests are presented in Tables 6 and 7 in the Appendix. Additional runs were completed to determine the kerf spacing required for interaction and excavation of material between the kerfs.

4.2 MECHANICAL CUTTER DEVICES

Testing of the combination of jet and mechanical cutting was of most significance since extrapolations of laboratory data have shown that the jet process alone, while technically feasible for excavating hard rock, is not cost effective because of prohibitively high energy requirements. The use of some mechanical breakage was expected to lower the overall energy requirements and preserve the advantages of using fluid jets for this purpose. Two types of mechanical cutters were used, a disc cutter, and a tungsten carbide button cutter of the type used on hard-rock tunnelling moles. Tests of both cutter types consisted of prescoring and weakening the rock face with the jets prior to the mechanical fracturing tests. Prior to testing, data was taken to determine

jet penetration as a function of feedrate, permitting the use of slot depth as a test variable. The depth was determined by selecting the appropriate value of feedrate from this curve. Kerf depth data is presented in Table 8 in the Appendix. Test parameters were as follows:

Slot depth (in):	0.25, 0.375
Slot spacing (in):	0.50, 0.75, 1.0
Cutter thrust (lb):	1500, 3000
Nozzle diameter (in):	0.008, 0.012
Jet pressure (psi):	65,000

It was originally planned to run the cutters in two locations, both between parallel kerfs, and inserted in a kerf with adjacent kerfs upon either side. Because of the flexibility of the cutter-wheel mounting structure and the crawler boom, and the irregularity of the rock face, it was impossible to keep the cutters positioned between the kerfs for the travel required; therefore, this portion of the test was deleted. The cutters would, however, readily follow the kerf when inserted into it. The disc cutter functioned satisfactorily in this manner for the majority of the anticipated tests. Wear of the cutter disc eventually caused it to be blunted to the point that it would not follow the kerf, necessitating deletion of 4 of the 24 test points, as shown in the data summary presented in Table 1, which indicates the percentage of material removed between two kerfs by the cutter action.

The tungsten carbide cutter design caused only minor localized compressive failure of the granite, with no extensive spalling of the rock between the kerfs; its use was discontinued after several preliminary runs. Additional runs were added to the tests for confirmation of the Phase I data in order to compensate for the deletion of the button cutter tests.

Modifications to the system, expected to eliminate the problems encountered with the present cutter designs, would be the use of harder material for the disc cutter and use of higher cutter thrust levels (necessitating redesign of the intensifier positioning system) for the button cutter.

Following completion of the above testing to verify machine performance requirements in the field, the rock fracturing system was returned to Bendix for minor repairs, then delivered to the U.S. Bureau of Mines, High Energy Test Facility, at Farmington, Minnesota.

Table 1 - Percentage of Material Removed Between Adjacent Kerfs by Disc Cutter Action

Nozzle Diameter (in)	Thrust (lb)	Kerf Depth (in.)					
		0.25			0.375		
		Kerf Spacing (in.)			Kerf Spacing (in.)		
		0.5	0.75	1.0	0.5	0.75	1.0
0.008	1,500	Not Run	Not Run	Not Run	95	90	35
	3,000	75	Not Run	40	90	100	60
0.012	1,500	65	75	25	95	95	65
	3,000	95	50	25	80	90	50
Spacing/Depth		2	3	4	1.33	2	2.66

Jet pressure:	65,000 psi
Disc cutter speed:	50 in/min
Jet feedrates:	50 in/min for 0.25 in. kerf depth (0.008 in. nozzle diameter)
	40 in/min for 0.375 in. kerf depth (0.008 in. nozzle diameter)
	200 in/min for 0.25 in. kerf depth (0.012 in. nozzle diameter)
	50 in/min for 0.375 in. kerf depth (0.012 in. nozzle diameter)

SECTION 5

SPECIFIC ENERGY ANALYSIS

5.1 DERIVATION OF ANALYSIS

The dependent variable of the experiments, as in the Phase I effort, was specific energy, the amount of energy required to remove a unit volume of rock. Specific energy was determined for single cuts, for kerfing, wherein interaction between successive cuts results in the excavation of the material between, and for rock removal by mechanical means wherein the jet energy was assumed to be the only energy input to the rock.

Specific energy was calculated from system operating parameters based on the calculated actual power level at the nozzle rather than hydraulic system input power, and, therefore, is not affected by the inefficiencies of the particular hydraulic system and intensifier used.

Derivation of the specific energy is as follows:

$$\text{Specific Energy} = \frac{\text{Power x Time}}{\text{Volume of Material Removed}} \tag{1}$$

The intensifier power delivered to the nozzle is given as

$$\text{Power} = 5\ (Q \times \Delta P) \tag{2}$$

Where power is expressed in ft-lb/min

Q = flow, in^3/sec

ΔP = nozzle pressure drop, psi

Since the system flow is governed by the nozzle area

$$Q = C_d\ A \sqrt{\frac{2g\ (\Delta P)}{\rho}} \tag{3}$$

where

Q = flow, in^3/sec

g = gravitational constant = 386 in/sec^2

ρ = fluid density = 0.0361 lb/in^3 for water (assumed incompressible)

ΔP = nozzle pressure drop, psi

C_d = assumed discharge coefficient = 0.75

A = nozzle orifice area, in^2

Since the total pressure head of the high-pressure fluid is converted to velocity head during its passage through the nozzle, the pressure drop is given as

$$\Delta P = (P - P_{ambient}) = P \tag{4}$$

where

P = nozzle supply pressure, psig

$P_{ambient}$ = 0 psig

Also,

$$A = \frac{\pi}{4} (N)^2 \tag{5}$$

where

N = nozzle diameter, inches

By combining equations (3), (4), and (5) and substituting into (2),

$$\text{Power} = 5\ C_d \left(\frac{\pi}{4} N^2\right) \left(\frac{2g\ P}{\rho}\right)^{1/2} \left(P\right) \tag{6}$$

Substituting numerical values gives

$$\text{Power} = 430.7\ N^2\ P^{1.5} \tag{7}$$

The time during which power is delivered is determined as follows:

$$\text{Time} = \frac{L}{F} \tag{8}$$

where

L = length of cut, in.

F = feedrate, ipm

The volume of material removed is determined by:

$$V = W \times D \times L \tag{9}$$

where

W = kerf width, in.

D = kerf depth, in.

This assumes a rectangular kerf cross section.

By substituting equations (7), (8) and (9) into equation (1) and cancelling the kerf lengths,

$$SE = \frac{430.7\ (N)^2\ (P)^{1.5}}{F\ W\ D} \tag{10}$$

where

SE = specific energy, ft-lb/in^3

N = nozzle diameter, in.

P = nozzle supply pressure, psig

F = feedrate, ipm

W = kerf width, in.

D = kerf depth, in.

The general equation (10) was used for calculation of all specific energies for this report. Further manipulation of the equation to accommodate specific processes, such as jet kerfing and mechanical wedging, are described in later sections dealing with these topics.

5.2 COMPARISON WITH PHASE I DATA

One of the primary purposes of the test series, in addition to verification of system performance in the field, was to provide some comparison with data from the laboratory testing conducted under Phase I of the present investigation. The Phase I effort, conducted by Bendix Research Laboratories under ARPA Contract No. H0210034, is described completely in the final report "Continuous High-Velocity Jet Excavation - Phase I." The laboratory testing yielded information regarding the specific energy for cutting a variety of rock types, including Barre granite, at jet supply pressures from 20,000 to 80,000 psi, using nozzle diameters from 0.008 to 0.0136 in., at feedrates from 50 to 900 ipm. Tests were completed for both single cuts and for kerfing runs wherein the material between two kerfs was removed by the action of the jet in cutting the second kerf. The conclusion of the report was that the specific energy of the jet excavation process was too high to permit practical commercialization. It was anticipated, however, that a reduction in the specific energy could be anticipated when cutting *in-situ* rock because of the compressive stress upon the rock, which was expected to facilitate excavation.

The field test series was planned to utilize test conditions which would permit direct comparison with selected tests from the laboratory series, as well as other areas which had not been fully explored in the laboratory tests. Test data from the field tests are presented in the appendix for the single cut and kerfing tests, respectively. Test results, indicating specific energies, are presented in Table 2.

The comparison of specific energy values from laboratory and field tests is presented in Table 3, which indicates that where test conditions were directly comparable, in all but one case the specific energy is lower for the *in-situ* testing. It should be noted, however, that a lower level of confidence can be associated with the field test results than with the laboratory tests because of reasons associated with the conduct of the tests. The foremost reason is associated with the procedures used to determine the kerf volume. For the laboratory tests, kerf volume was determined directly by measuring the volume of sand-like emery material required to fill the kerf over the length of the cut. This method was not practical for the field testing because cuts were made upon a vertical surface. For this reason, width and depth measurements were taken directly at a series of intervals along the kerf and a rectangle used to approximate the kerf cross section, for energy calculations, resulting in a larger potential for error than that of the laboratory tests. Additionally, the rock face was not flat, as were the laboratory test samples, resulting in a variation in jet standoff distance and angle of incidence which was not present in the laboratory. Variation in standoff distance and angle of incidence caused by the motion of the

Table 2 - Field Test Specific Energy Values

Supply Pressure (psi)	Nozzle Diameter (in)								
	0.008						0.012		
	Feedrate (in/min)						Feedrate (in/min)		
	50		150		300		50	150	300
30,000	365,385 (30,229)	366,695 (30,338)	203,164 (16,808)	137,273 (11,357)	184,766 (15,286)	68,011 (5,627)	482,584 (39,926)	194,890 (16,124)	66,607 (5,511)
50,000	443,302 (36,676)	348,782 (28,856)	205,785 (17,025)	347,054 (28,713)	101,190 (8,372)	157,172 (13,003)	959,875 (79,413)	275,164 (22,766)	155,963 (12,903)
65,000	836,628 (69,217)	1,031,614 (85,349)	204,329 (16,905)	281,975 (23,329)	232,113 (19,203)	171,936 (14,225)	955,913 (79,086)	468,415 (38,753)	316,167 (26,157)

Specific energy units: ft-lb/in^3 (J/cm^3)

Table 3 - Comparison of Specific Energy Values for Laboratory and *In Situ* Tests

Pressure psi	Test Site	Nozzle Diameter (in)							
		0.008						0.012	
		Feedrate (in/min)						Feedrate (in/min)	
		50		150		300		50	150
50,000	*In-Situ*	443,302 (36,676)	348,782 (28,856)	205,785 (17,025)	347,054 (28,713)	101,190 (8,372)	157,172 (13,003)	959,875 (79,413)	275,164 (22,766)
	Lab	1,077,575 (89,151)	1,010,267 (83,578)	443,377 (36,682)	532,053 (44,018)	224,495 (18,573)	224,495 (18,573)	1,063,975 (88,026)	251,227 (20,785)
65,000	*In-Situ*	836,628 (69,217)	1,031,614 (85,349)	204,329 (16,905)	281,975 (23,329)	232,113 (19,203)	171,936 (14,225)	955,913 (79,086)	468,415 (38,753)
	Lab	1,364,285 (112,871)	1,227,857 (101,5[illegible]4)	818,571 (67,723)	545,714 (45,149)	Not Run	Not Run	1,049,822 (86,855)	574,871 (47,560)

Specific energy units: ft-lb/in^3 (J/cm^3)

jet nozzle in a large-radius arc were on the order of 0.1 in. and ±3 deg respectively, over the length of the measured kerf. These variations were not expected to provide a significant error in the test results. It appears improbable, however, that a more rigorous determination can be made of the specific energy of excavation of *in-situ* rock structures, because of the conditions described above.

A comparison of the results of the kerfing tests is presented in Table 4. The spacing recorded is the approximate distance between two jet-cut kerfs where the second cut completely removed the material between. A slight decrease in specific energy is experienced with the *in-situ* rocks; however, more testing would be indicated in this area for the reasons mentioned previously with regard to single-cut testing. A significant development from these tests is the determination that, by using two jets, a relatively wide kerf (0.375 in.) can be cut with this method at the higher pressures, providing increased width for insertion of wedge wheels or cutters into the rock face to reduce the overall specific energy of the process. This determination was not incorporated in succeeding tests of the mechanical breakage devices. The specific energies for the kerfing runs were calculated for the second cut only, under the assumption that the material removed by the kerfing cut would be dislodged into the kerf left by the previous cut. Although an initial single cut would be required to provide a volume for the dislodged rock from the next cut, the energy required for the initial cut would be insignificant when averaged over many succeeding cuts, as would be the case in an actual jet excavation system.

5.3 KERF DEPTH

A series of tests were run to determine kerf depth as a function of feedrate in order to determine the feedrate required to give a certain depth for use in tests of the mechanical breakage devices. Data from

Table 4 - Jet Kerfing Test Data (No Mechanical Assist)

Test Site	Pressure (psi)	Feedrate (in/min)	Nozzle Diameter (in)	Distance Between Jet Cuts (in)	Specific Energy	
					($ft\text{-}lb/in^3$)	(J/cm^3)
Lab	50,000	900	0.008	0.093	46,623	3,857
In-Situ	30,000	300	0.008	0.100	45,960	3,802
		300	0.008	0.100	34,723	2,873
	65,000	50	0.008	0.375	96,091	7,950
		50	0.008	0.375	104,411	8,638
		50	0.012	0.350	107,804	8,919

the test runs is presented in Table 8 in the appendix. A curve of slot depth versus feedrate is presented in Figure 2, along with the specific energy required to produce the slot. The curves are based on the average of two test runs completed at each feedrate of 50, 100, 150, 200, 300 and 400 in. per minute at a pressure of 65,000 psi using a 0.012-in. diameter nozzle. Additional tests were run using an 0.008-in. diameter nozzle, indicating that feedrates of 40 and 50 in. per minute would yield cuts having depths of 0.38 and 0.25 in., respectively, at 65,000 psi. Since these were the depths chosen for use in the cutter tests, no additional runs were made with the 0.008-in. diameter nozzle.

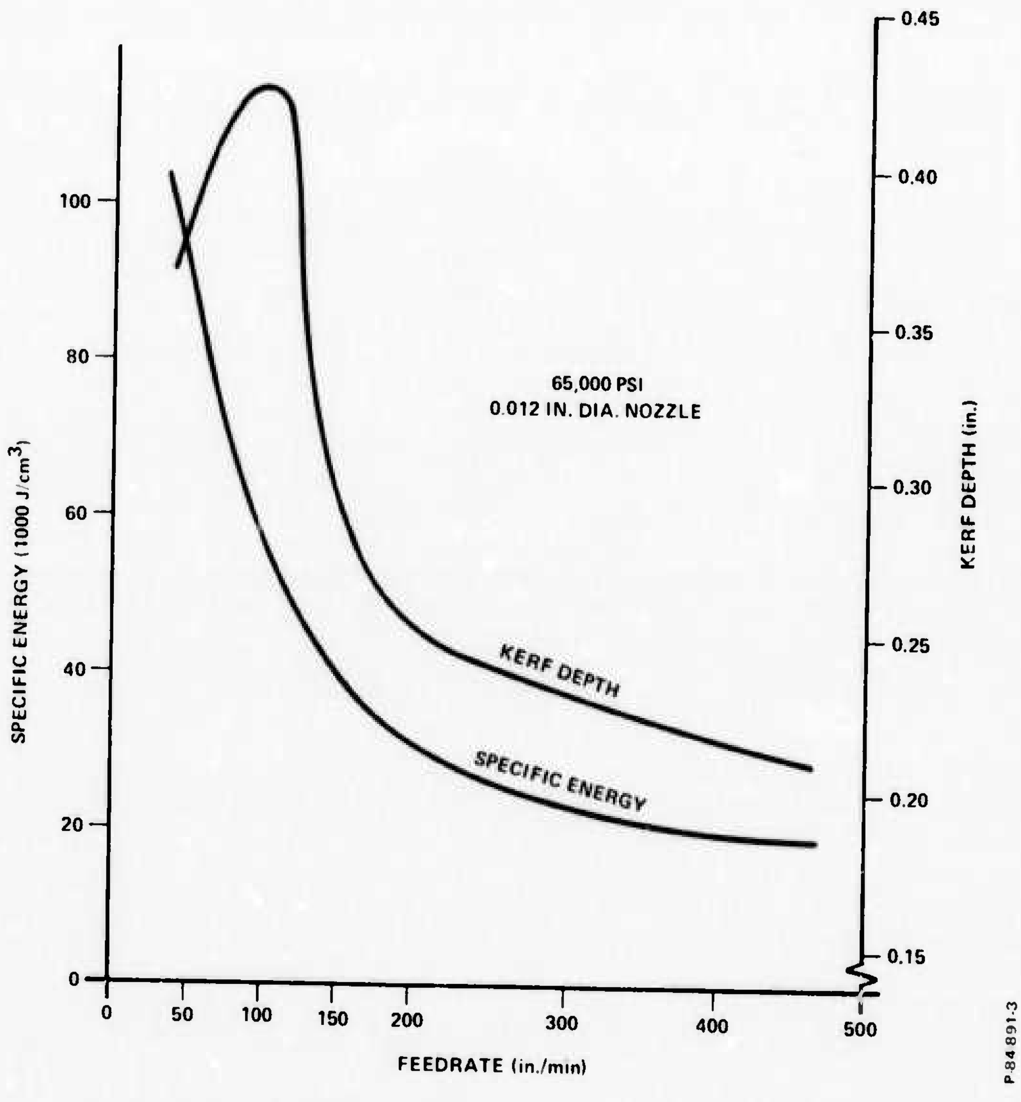

Figure 2 - Specific Energy and Kerf Depth Versus Feedback

As shown in Figure 2, the curves of specific energy and kerf depth, as functions of feedrate, have essentially the same form, except at the lower feedrates, where the curve of kerf depth drops off. Since only two test runs were completed at each feedrate tested, the possibility exists that the high kerf depth produced at a feedrate of 100 in. per minute may be the result of a flaw in the rock face or some other extraneous factor, in which case the kerf depth curve would have approximately the same shape as the specific energy curve. Another possible cause is that at lower feedrates, the cutting action of the jet is less efficient because of interference with fluid rebounding from the bottom of the kerf. Since the rebounding fluid decreases the momentum of the cutting jet, a shallower kerf depth is produced. This effect has been observed in laboratory tests on common industrial materials. No correlation with Phase I laboratory tests can be made since kerf depth was not recorded for the Phase I testing because kerf volume was determined by direct measurement. Further testing would be required to determine with greater certainty the shape of the kerf depth curve at feedrates less than 150 in. per minute.

The shape of the specific energy curve presented in Figure 2 follows closely the data generated in the Phase I testing on laboratory samples. The magnitude of the curve appears lower than that of laboratory tests, although a rigorous comparison is impossible since, during the laboratory test series, all test runs at feedrates over 150 ipm were made with an 0.008-in. diameter nozzle, which was determined during the laboratory test phase to decrease the specific energy of the cut compared to that resulting from the use of a 0.012-in. nozzle. As shown in Figure 3, the specific energy for the runs made on the *in-situ* rock with the 0.012-in diameter nozzle is approximately equal to that which would be obtained with the 0.008-in. diameter nozzle on the laboratory samples at a comparable pressure.

5.4 MECHANICAL FRAGMENTATION TESTS

Two mechanical fragmentation devices were designed and included in the jet excavation system. The purpose of these devices was to allow the conduct of baseline tests regarding the feasibility of removing by mechanical means rock which had been previously scored and weakened by the action of high-pressure jets. Since the mechanical breakage occurs at a much lower specific energy than the jet excavation process, it was expected that the combined processes would have a lower specific energy than the jet excavation alone. Because of the interaction of many variables in the combined excavation process, including jet pressure and nozzle diameter, kerf depth and spacing, jet and cutter feedrates and cutter configuration, and path, as well as the absence of any data regarding the combination of these processes, a full-scale laboratory test series would be required to predict the optimum conditions for the combined processes. In the absence of such studies, the design and testing of the mechanical breakage devices was concluded as part of the present effort.

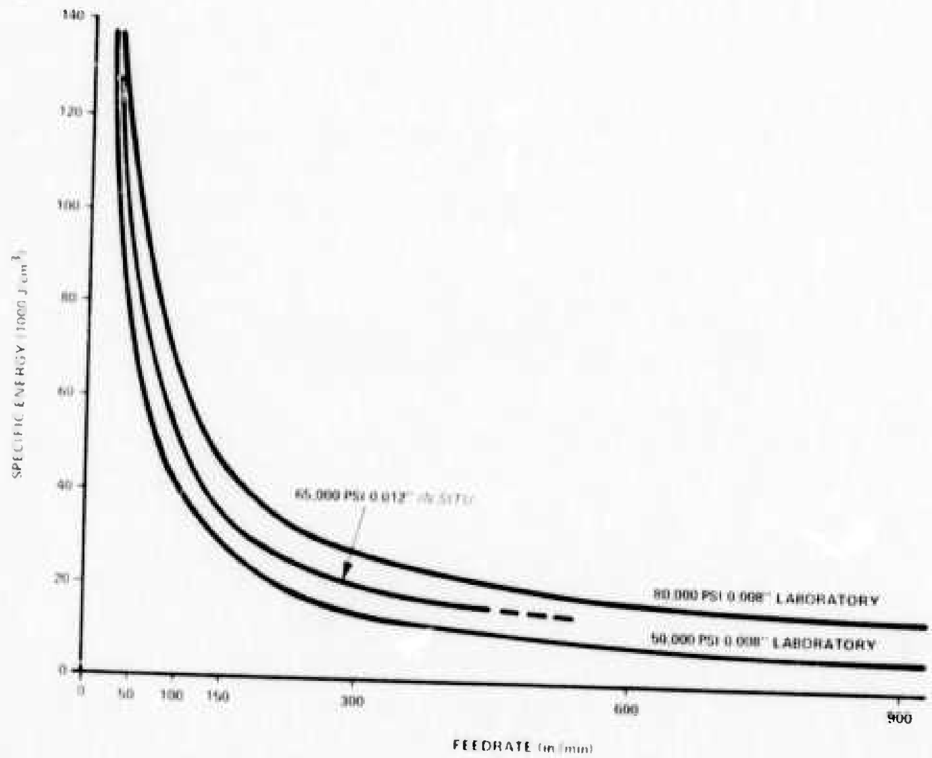

Figure 3 - Specific Energy as a Function of Feedrate for Laboratory and *In-Situ* Tests

Two cutter designs were completed for the fragmentation system prototype - a disc-type wedge cutter and a cutter design employing tungsten carbide balls to simulate the button cutters employed in conventional tunnel moles. Test plans are described in Section 3, which indicates in detail the results of the tests.

Specific energies for the test runs utilizing the disc cutter are presented in Table 5. The energy required to move the cutter disc and impart force against the wall was not measured for these preliminary tests, so that the jet energy was assumed to be the total energy input to the rock for the excavation. As described in Section 5.2 regarding kerfing tests, it was assumed that the material removed by the cutter would be dislodged into the kerf produced by the last pass, so that one jet kerf followed by one cutter pass would remove the rock between the jet kerf and the kerf produced by the last cutter pass. The energy required to produce the first jet kerf to allow removal of rock by the second pass would be insignificant when averaged over a large number of passes.

The specific energy values presented in Table 5 indicate some improvement over pure jet kerfing using the same pressures, feedrates and nozzle sizes. A direct comparison between non-assisted and assisted

Table 5 - Specific Energy Values for Disc Cutter Tests

Nozzle Diameter (in)	Thrust (lb)	Kerf Depth (in)					
		0.25			0.375		
		Kerf Spacing (in)			Kerf Spacing (in)		
		0.5	0.75	1.0	0.5	0.75	1.0
0.008	1500	Not Run	Not Run	Not Run	64,112 (5,304)	45,116 (3,733)	87,009 (7,199)
	3000	97,450 (8,062)	Not Run	91,360 (7,558)	67,674 (5,599)	40,604 (3,359)	50,755 (4,199)
0.012	1500	63,249 (5,233)	36,544 (3,023)	82,224 (6,803)	115,402 (9,548)	76,935 (6,365)	84,332 (6,977)
	3000	43,276 (3,580)	54,816 (4,535)	82,224 (6,803)	137,040 (11,338)	81,209 (6,719)	109,632 (9,070)
Spacing/Depth		2	3	4	1.33	2	2.66

Specific energy units: $ft\text{-}lb/in^3$ (J/cm^3)
Jet pressure: 65,000 psi
Disc cutter speed: 50 in/min
Jet feedrates: 50 in/min for 0.25 in. kerf depth (0.008 in. nozzle diameter)
40 in/min for 0.375 in. kerf depth (0.008 in. nozzle diameter)
200 in/min for 0.25 in. kerf depth (0.012 in. nozzle diameter)
50 in/min for 0.375 in. kerf depth (0.012 in. nozzle diameter)

jet kerfing can be made by observing data run at 65,000 psi with both 0.008- and 0.012-inch nozzles at a feedrate of 50 inches per minute. As shown in Table 4 two unassisted jet kerfing runs were made with the 0.008-inch nozzle and one with the 0.012-inch nozzle at cut spacings of 0.375 and 0.350 inch, respectively. These cut spacings were the maximums for which complete excavation of the material between the cuts occurred for the pressures and feedrates employed. Observed specific energies were 7950 and 8638 J/cm^3 for the 0.008-inch nozzle runs and 8919 J/cm^3 for the run using the 0.012-inch nozzle. A feedrate of 50 inches per minute was employed for the tests in Table 5 to produce a 0.25-inch deep kerf using the 0.008-inch nozzle, and a 0.375-inch deep kerf using the 0.012-inch nozzle. Similar cut depths were obtained in the unassisted jet kerfing runs, data for which is presented in Table 7, Appendix A. Kerf spacing values of 0.5, 0.75 and 1.0 inch were used for the mechanically assisted kerfing tests; all spacings employed were above 0.375 inch, the maximum spacing for which complete excavation could be expected for the unassisted jets. Test runs were not completed for all conditions due to the aforementioned dulling of the disc cutter, after which it was unable to follow the jet kerf.

As can be seen from the data of Table 5, the two runs completed with the 0.008-inch diameter nozzle exhibited specific energies of 8062 and 7558 J/cm^3, as compared with 8638 and 7950 J/cm^3 for the unassisted jet kerfing tests of Table 4. It is expected that a greater decrease in specific energy could have been obtained had this series of tests been run before the disc cutter became dulled. For comparison, the tests with the 0.008-inch nozzle at a 0.375-inch kerf depth (produced by a 40-inch-per-minute feedrate) were run with the cutter in its sharpest condition.

The average specific energy for the six test runs of Table 5 which employed the 0.012-inch nozzle at 50-inch-per-minute feedrate was 8336 J/cm^3, which is less than the 8919 J/cm^3 obtained for the unassisted jet kerfing tests. In addition, the two runs conducted at a kerf spacing of 0.75 inch averaged 6542 J/cm^3, approximately a third less than the unassisted value.

As mentioned previously, the test results indicate some improvement over pure jet kerfing when using the mechanical assistance. The limited number of test runs as well as the difficulties of kerf measurement in the field preclude, however, the drawing of rigorous conclusions regarding the test data. It appears that further testing would be required to verify the indications of this test series regarding the use of mechanically assisted jet excavation, as well as to determine whether other combinations of process parameters would be more advantageous for reduction of specific energy of the process. Observation of the amount of material removed by the process indicates, as shown in Table 1, that the percentage of the material removed tends to be a maximum, for the majority of the tests completed, at the point where the kerf spacing was twice the kerf depth. Additionally, for testing utilizing the 0.008-inch diameter nozzle and 0.375-inch kerf spacing, which was completed first before the cutter disc became dulled, the specific energy decreased with increasing cutter force.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

Completion of *in-situ* cutting tests using the Bendix-designed excavation system prototype demonstrated that lower single-cut specific energies were obtained for excavation of *in-situ* Barre granite by high-pressure fluid jets than were obtained during Phase I laboratory testing.

The data taken did not permit a conclusive determination of reductions in specific energies of excavation by jet kerfing and mechanical fragmentation on *in-situ* rock.

Further testing of the combination of jet/mechanical interaction should explore breakage and specific energy as functions of kerf depth and spacing, jet operating parameters, jet and cutter feedrates and cutter configuration, in order to optimize the performance of this method of rock excavation.

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APPENDIX A

FIELD TEST DATA

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Table 6 - Phase I Confirmation

Test Number	Test Sequence	Nozzle Diameter (in)	Pressure (ksi)	Feedrate (in/min)	Depth of Kerf (in)						Width of Kerf (in)					
					1	2	3	4	5	Avg.	1	2	3	4	5	Avg.
1	17			50	0.06	0.07	0.09	0.12	0.15	0.098	0.10	0.07	0.06	0.07	0.10	0.080
2	6		30	150	0.02	0.02	0.09	0.09	0.03	0.050	0.09	0.08	0.10	0.10	0.10	0.094
3	13			300	0.05	0.04	0.02	0.06	0.02	0.038	0.05	0.10	0.06	0.05	0.08	0.068
4	10			50	0.20	0.15	0.12	0.16	0.16	0.158	0.09	0.08	0.07	0.09	0.10	0.086
5	11		50	150	0.10	0.08	0.14	0.09	0.11	0.104	0.07	0.05	0.16	0.08	0.12	0.096
6	7			300	0.09	0.17	0.13	0.11	0.04	0.108	0.10	0.10	0.08	0.10	0.09	0.094
7	2			50	0.08	0.20	0.20	0.10	0.20	0.156	0.06	0.07	0.06	0.08	0.08	0.070
8	18		65	150	0.15	0.17	0.10	0.21	0.18	0.162	0.10	0.12	0.09	0.09	0.06	0.092
9	8	0.008		300	0.05	0.03	0.10	0.13	0.10	0.082	0.07	0.06	0.11	0.10	0.06	0.080
10	5			50	0.05	0.05	0.02	0.12	0.07	0.062	0.18	0.12	0.10	0.13	0.10	0.126
11	4		30	150	0.08	0.05	0.02	0.12	0.10	0.074	0.10	0.08	0.09	0.08	0.12	0.094
12	3			300	0.02	0.05	0.10	0.05	0.05	0.054	0.10	0.10	0.15	0.10	0.20	0.130
13	15			50	0.20	0.20	0.15	0.15	0.24	0.188	0.06	0.09	0.09	0.12	0.11	0.094
14	1		50	150	0.05	0.05	0.20	0.05	0.05	0.080	0.07	0.05	0.10	0.05	0.10	0.074
15	12			300	0.11	0.06	0.06	0.10	0.10	0.086	0.06	0.06	0.07	0.09	0.10	0.076
16	16			50	0.23	0.18	0.15	0.15	0.28	0.198	0.15	0.15	0.12	0.11	0.15	0.136
17	9		65	150	0.10	0.10	0.10	0.18	0.22	0.140	0.10	0.10	0.07	0.09	0.09	0.090
18	14			300	0.09	0.08	0.10	0.12	0.15	0.108	0.08	0.08	0.09	0.09	0.07	0.082
19	19			50	0.13	0.20	0.11	0.09	0.10	0.126	0.09	0.06	0.20	0.08	0.10	0.106
20	20		30	150	0.06	0.14	0.11	0.09	0.10	0.104	0.10	0.10	0.08	0.15	0.10	0.106
21	21			300	0.10	0.12	0.06	0.08	0.08	0.088	0.11	0.18	0.25	0.15	0.15	0.168
22	22			50	0.32	0.35	0.30	0.40	0.35	0.344	0.05	0.05	0.04	0.03	0.04	0.042
23	23	0.012	50	150	0.30	0.30	0.22	0.18	0.40	0.280	0.08	0.06	0.04	0.05	0.07	0.060
24	24			300	0.18	0.18	0.22	0.19	0.18	0.190	0.08	0.08	0.10	0.08	0.05	0.078
25	25			50	0.48	0.37	0.50	0.42	0.47	0.448	0.07	0.04	0.05	0.04	0.04	0.048
26	26		65	150	0.22	0.44	0.35	0.30	0.28	0.318	0.05	0.04	0.05	0.04	0.05	0.046
27	27			300	0.28	0.32	0.24	0.21	0.24	0.258	0.04	0.05	0.03	0.05	0.04	0.042

Test numbers 1 through 18 run on 26 June 1973; test numbers 19 through 27 run on 28 June 1973.

Table 7 - Pure Jet Kerfing

Pressure (ksi)	Feedrate (in/min)	Nozzle Diameter (in)	Spacing (in)	Date	Depth of Kerf (in)						Width of Kerf (in)					
					1	2	3	4	5	Avg	1	2	3	4	5	Avg
30	300	0.008	0.100	6-26-73	0.090	0.110	0.100	0.090	0.100	0.0980	0.113	0.111	0.111	0.088	0.107	0.1060
				6-28-73	0.125	0.125	0.125	0.125	0.125	0.1250	0.110	0.110	0.110	0.110	0.110	0.1100
65	50	0.008	0.375	6-26-73	0.220	0.280	0.270	0.160	0.210	0.2280	0.392	0.427	0.408	0.423	0.436	0.4172
				6-28-73	0.250	0.250	0.250	0.250	0.250	0.2500	0.350	0.350	0.350	0.350	0.350	0.3500
65	50	0.012	0.375	6-26-73	---	---	---	---	---	---	0.375	0.375	0.375	0.375	0.375	0.3750
				6-28-73	0.350	0.350	0.350	0.350	0.350	0.3500	0.350	0.350	0.350	0.350	0.350	0.3500

Table 8 - Slot Depth Versus Feedrate

Nozzle Diameter (in)	Feedrate (in/min)	Date	Depth of Kerf (in)						Width of Kerf (in)					
			1	2	3	4	5	Avg	1	2	3	4	5	Avg
0.012	50	6-26-73	0.41	0.39	0.40	0.42	0.36	0.396	0.049	0.049	0.047	0.048	0.041	0.0468
	100		0.43	0.34	0.40	0.37	0.39	0.386	0.047	0.044	0.047	0.047	0.048	0.0466
	150		0.32	0.42	0.24	0.31	0.30	0.318	0.050	0.045	0.043	0.046	0.044	0.0456
	200		0.25	0.29	0.28	0.30	0.25	0.274	0.039	0.036	0.045	0.039	0.043	0.0404
	300		0.28	0.26	0.30	0.29	0.30	0.286	0.037	0.044	0.036	0.048	0.044	0.0418
	400		0.24	0.19	0.21	0.25	0.21	0.220	0.039	0.039	0.042	0.039	0.038	0.0394
	50	6-28-73	0.40	0.32	0.50	0.30	0.35	0.374	0.05	0.05	0.04	0.04	0.05	0.046
	100		0.49	0.47	0.45	0.42	0.48	0.462	0.06	0.05	0.05	0.07	0.05	0.056
	150		0.25	0.28	0.30	0.26	0.26	0.270	0.05	0.05	0.06	0.04	0.05	0.050
	200		0.25	0.21	0.20	0.20	0.22	0.216	0.06	0.06	0.05	0.06	0.07	0.060
	300		0.14	0.21	0.24	0.22	0.16	0.194	0.05	0.06	0.05	0.06	0.06	0.056
	400		0.25	0.19	0.23	0.15	0.23	0.210	0.05	0.05	0.05	0.04	0.04	0.046
0.008	50	6-26-73	0.26	0.25	0.25	0.30	0.25	0.262	0.047	0.045	0.041	0.053	0.055	0.0482
	40		0.38	0.39	0.36	0.37	0.39	0.378	0.049	0.048	0.046	0.050	0.052	0.0490

Pressure: 65,000 psi